Creation and verification of a controlled experimental stimulus for investigating selected perceived spatial attributes

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ABSTRACT

In order to undertake controlled investigations into perceptual effects that relate to the interaural cross-correlation coefficient, experiment stimuli that meet a tight set of criteria are required. The requirements of each stimulus are that it is narrow band, normally has a constant cross-correlation coefficient over time, and can be altered to cover the full range of values of cross-correlation coefficient, including specified variations over time if required. Stimuli created using a technique based on amplitude modulation are found to meet these criteria, and their use in a number of subjective experiments is described.

1. INTRODUCTION

In recent years, there has been increased interest in the interaural cross-correlation coefficient (IACC) and its relationship with the perceived spatial impression that is created by recorded and reproduced sound. Previous research into psychoacoustics has indicated that the IACC may be related to the auditory perception of width or size [1, 2, 3]. This research has been developed in the field of concert hall acoustics in order to design measurements that are thought to relate to apparent source width and envelopment [4, 5, 6]. More recently, attempts have been made to utilise similar measurements in sound recording and reproduction with the aim of predicting the spatial performance of various recording [7, 8, 9, 10] and reproduction [11, 12, 13, 14] techniques.

The IACC is based on the simple cross-correlation coefficient (CCC) calculation shown in Equation 1 that essentially measures the similarity of two signals.

Equation 1

\[ CCC(\tau) = \left( \frac{\int_{t_1}^{t_2} x(t)y(t+\tau)dt}{\left(\int_{t_1}^{t_2} x^2(t)dt\right)^{1/2}\left(\int_{t_1}^{t_2} y^2(t)dt\right)^{1/2}} \right) \]

where \( x \) and \( y \) are the two signals whose correlation is to be calculated.
\( t1 \) and \( t2 \) are the period over which the correlation is calculated. 
\( \tau \) is an offset between the two signals under measurement.
(Adapted from [15])

The CCC may be applied to any two signals, though for the purpose of the IACC it is employed to analyse a pair of binaural signals (the signals that reach the ears of a listener or a head and torso simulator). In this case, \( \tau \) is usually measured over a range that is large enough to encompass the maximum interaural time difference that is caused by the physical separation of human ears, typically ±1 ms. The final IACC value is then taken to be the maximum absolute value across the range of \( \tau \), as shown in Equation 2.

Equation 2

\[
IACC = \left| CCC(\tau) \right|_{max}, \text{ for } -1\text{ms} < \tau < +1\text{ms}
\]
(Adapted from [4])

Previous research indicates that if a simple stimulus whose IACC value is close to 1 is fed to the ears, a single scene component will be perceived that is relatively narrow. As the IACC of the signal is reduced, the scene component will be perceived to increase in size or width, until a point at which it may be perceived as two separate scene components, one positioned at each ear [1, 2].

Research has suggested that for more complex stimuli that are perceived to consist of a number of scene components with reverberation (such as a group of musical instruments in a concert hall), the measured IACC of each component of the signal is related to the perceived width of the respective scene components [16]. Whilst analysis of the properties of sounds based on the scene components to which they are related may be more externally valid, it is a more complex task. Therefore, for the purposes of this paper, the scope is limited to simple stimuli that will be perceived as a single scene component without reverberation. In this case, references to changes in the width of a sound refer to a subjective effect similar to that described in the previous paragraph.

Even though measurement techniques based on the IACC are becoming frequently used, there are arguments against its practicality and there are also a number of fundamental factors that have not yet been fully addressed.

For instance, the measured IACC values of signals that contain solely audio frequencies of below approximately 500 Hz generally have little variance compared to signals that contain solely higher audio frequencies and rarely differ greatly from a value of 1 [17]. However, research has shown that stimuli with an audio frequency of 60 Hz or lower can cause significant spatial impression [18]. It is possible that the human auditory system compensates for the lack of decorrelation at low frequencies [19], and therefore it is important to investigate whether the relationship between a certain IACC value and the perceived width or size is dependent on the audio frequency of the signal.

In addition to this, measurements of continuous stimuli that are sounded in reverberant acoustical environments show that the IACC can vary greatly over time [16]. It is apparent that until now few studies have been conducted into the perceived spatial impression of variations in the IACC over time. It is possible that this perceptual factor is also dependent on the audio frequency.

Finally, a number of attempts have been made to quantify the threshold of changes of IACC that are perceivable [20, 21]. However, if the perception of IACC is frequency-dependent then it is likely that the just-noticeable-difference (JND) thresholds are also frequency-dependent and therefore this may require further research.

Whilst useful measurements can be made with metrics based on the basic IACC calculation, if an objective measurement is required that accurately predicts the perceived spatial attributes of a wide range of signal types and in a wide range of situations, then further research into factors such as these is required.

One reason for the lack of detailed research into these factors is that it is difficult to create a stimulus with sufficiently tightly controlled parameters. In order to accurately test the parameters discussed above, stimuli are required that differ in terms of the objective parameter that is under investigation, whilst differences in all other objective parameters are limited as much as possible [22]. In addition, it is necessary that these stimuli meet stringent requirements in other aspects.

This paper sets out the specific requirements of such a stimulus, suggests a possible synthesis technique, and validates the properties of the stimuli thus generated.
2. STIMULI REQUIREMENTS

In order to accurately examine the relationship between the IACC and its perceived effect at a range of audio frequencies, a stimulus with the following properties is required.

Firstly, the stimulus needs to have a narrow bandwidth in order to enable the examination of factors that may be dependent on the audio frequency. The method of creating the stimuli must also be applicable in a similar manner across a wide range of frequencies, in order to enable direct comparison of results in different frequency ranges. An ideal narrow-band signal would consist of a single sinusoidal frequency component, however it is impossible to create a low IACC at a wide range of frequencies by the use of a single sine tone. As it is known that the perceived effect of stimuli differs depending on whether the frequency components fall within a single critical band [23], then this seems a reasonable limit for the bandwidth of the stimuli. Using the research of Glasberg and Moore into the auditory filter shapes, this gives a bandwidth of approximately 35 Hz at a centre frequency of 100 Hz rising monotonically to a bandwidth of approximately 1000 Hz at a centre frequency of 10 kHz [24]. Therefore a reasonable target for the bandwidth of the experimental stimulus is approximately 35 Hz at low frequencies, with the option that this bandwidth can increase at higher frequencies.

Secondly, the stimulus needs to have a constant IACC over time. If the IACC of the stimulus varied over time, it would make it difficult to relate the perceived result to a specific IACC value. For instance, with a stimulus whose IACC varies over time, it is not known what rate of change is perceivable, or whether the judgements made by the subject relate to the average, maximum or minimum value. In addition, this attribute is particularly important when testing the JND thresholds of the IACC, as variations in the IACC over time may obscure perceivable differences between two stimuli with slightly different IACC values, as noted by Gabriel and Colburn [25].

Thirdly, in order to examine the full effect of the IACC, it is important to be able to create stimuli that have any of the full range of values from +1 to 0. In addition, if the stimulus is required for use in investigating the JND of the IACC, it is necessary to be able to control the IACC in as fine steps as possible so that stimuli can be created whose IACC differs by less than the JND. In addition to being able to accurately control the IACC of the stimuli to have any value, it should be possible to vary the IACC without causing any other changes in the stimuli. If a change in the IACC caused other perceivable variations in the stimuli, this would add a confounding variable to any experiments, meaning that judgements based on similarity or difference could be made based on other perceived attributes, such as the pitch, timbre or loudness of the stimuli as opposed to those attributes that are directly affected by the IACC.

It is unlikely that it is possible to vary the IACC of a stimulus without causing any other physical attributes to be altered. In this case, it is important to minimise the variations in the other attributes as much as possible, and to take the possibility of confounding variables into account in the experiment design and analysis.

Finally, in order to investigate the temporal characteristics of IACC perception, it is necessary to be able to create stimuli that contain controlled variations in the IACC over time. Ideally, it would be possible to create a wide range of variations in IACC including sinusoidal, linear and discrete step variations, and to be able to create these variations at a range of rates and magnitudes. The more flexible the method of creating the stimuli is, the more likely it is that a complete picture of the perceptual response can ultimately be obtained. It would be useful to be able to create these deliberate variations in IACC over time without introducing any other perceivable changes in the stimuli, for the reasons discussed above. However, as before, it is unlikely that this can be achieved and therefore the other perceivable changes must be limited as much as possible and taken into account in the experiment design and analysis.

3. PROBLEMS WITH COMMONLY USED STIMULI

3.1. Representative programme material

In order to be as externally valid as possible (i.e. to be directly applicable to the sound recording and reproduction systems to which the research into IACC may be applied), it would be preferable to use programme material that is typical for the recording or reproduction system under test, such as musical or speech stimuli. This type of stimulus has been used
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previously in experiments that have investigated factors relating to the IACC [26, 27, 28, 29].

However, it is impossible to find representative programme material that is sufficiently controlled to meet the criteria set out in Section 2. For instance, programme material is generally complex including a wide frequency range and a combination of transient and sustained components which could have a wide range of different perceivable spatial attributes. In addition, programme material usually contains a number of sound sources or scene components and this complexity means that it would be difficult for the subject to accurately judge each of the separately perceivable components, resulting in the potential for errors or for components to be overlooked. It is possible to modify the programme material to meet some of the criteria outlined in Section 2, such as using filters to limit the frequency range, but such modifications will reduce the external validity. In addition to this, it is very unlikely that programme material will have a constant IACC and it would be very difficult if not impossible to create musical stimuli with a wide range of values of IACC whilst limiting other perceivable variations.

As it seems that it is impossible to accurately control the parameters of representative programme material, an artificial stimulus is required use in the subjective experiments.

3.2. Noise stimuli

A stimulus that has been commonly used for investigating the perception of IACC is a noise signal [1, 2, 3, 25, 30]. Noise stimuli have the advantage over representative programme material that the spectral content can be accurately controlled, and stimuli with a wide range of IACC values can be created [3]. However, the main problem with the use of noise stimuli is that the IACC can vary a great deal over time due to the random nature of noise. In addition to this, the mean of the measured IACC of a noise stimulus can vary depending on the window length that is used in the measurement (t1 to t2 shown in Equation 1).

For instance, a white noise stimulus with a rectangular probability density function was created and then filtered with a 1/3rd octave filter centred on 1 kHz. Measurements were then made of this stimulus by using a series of IACC calculations with window lengths ranging from 0.5 to 0.01 seconds that overlapped by half the window length. Selected results are shown in Figure 1.

As can be seen in Figure 1, the amount of variation in the measured IACC over time and the mean IACC value of the filtered noise stimulus depend on the window length used in the measurement. With a
longer window length, the mean IACC value is lower and the variation over time is less (i.e. for a window length of 0.25 seconds the mean value is approximately 0.1 and the range is from approximately 0.05 to 0.2). With a shorter window length, the mean IACC value is higher and the variation over time is greater (i.e. for a window length of 0.01 seconds the mean value is approximately 0.5 and the range is from approximately 0.1 to 0.9).

It is apparent from the shorter window measurement that the IACC of the noise stimuli varies greatly over time, and even the variation shown in the measurement with a 0.25 second window may be large enough to affect judgements of the JND. Whilst this indicates that noise stimuli may not be suitable, it is important to estimate the most perceptually relevant time window to use in the measurement before a firm conclusion can be reached.

### 3.3. Estimation of the optimum time window

It appears from the literature that a number of studies have been conducted into related topics that give a wide range of opinions about the time constants and temporal response of binaural perception, and that it may be dependent on the audio frequency and the individual subject. It must be noted that the majority of the research conducted into the temporal response of binaural perception has been focused on the subject of binaural masking. Whereas this may be related to the IACC and the perception of width or size, it is not necessarily directly relevant.

Grantham and Wightman investigated the effect of a time-varying IACC on binaural masking, and concluded that there was a deterioration in the investigated parameter above a rate of variation of the IACC of approximately 4 Hz [31]. They found that the results were dependent on the subject and on frequency, and modelled the results using a temporal integration window with a range of between 44 and 243 ms.

A more recent study investigated the binaural temporal response using a technique that was described as binaural gap detection [32]. This involved placing a short segment of a noise stimulus with an IACC of 0 in the middle of a noise stimulus with an IACC of 1. From this experiment, it was estimated that the length of the binaural temporal window that matched the empirical results most accurately was between 140 and 210 ms.

Boehnke and colleagues furthered this research by using binaural gap detection with stimuli that contained a range of IACC values for the base and gap components [33]. They also estimated the optimum binaural temporal window that matched their results, and found that the mean values over the different stimuli ranged from approximately 35 to 150 ms depending on the subject.

Therefore, from the published research it appears that a suitable window length to use in IACC measurements is within the range of approximately 35 to 243 ms, and is dependent on both the subject and the spectral content of the stimuli.

The authors of this paper have also considered an alternative approach to determine the optimum window length for IACC measurements. Previous research has indicated that the length of the window has a bearing on the minimum frequency of the fluctuations in interaural time and level difference above which affect the measured IACC [16]. A longer window will cause fluctuations of a lower fluctuation frequency to affect the measured IACC, whereas a shorter window will mean that only more rapid fluctuations will affect the measured IACC. This attribute can be employed to separate those fluctuations that will be perceived as movement from those that will alter the stationary spatial attributes of the stimulus. Therefore the length of the window used in the IACC calculation can be set to match the data that is available on the maximum rate of fluctuations in interaural time and level difference that are perceivable.

Informal experimentation has shown that large fluctuations in interaural time difference are perceived as a stationary wide source, as opposed to movement, when the fluctuation frequency is around 15 to 20 Hz (which is similar to the results of Grantham and Wightman [34]). This equates to a rectangular measurement window with a length of approximately 50 to 70 ms, which is within the range found by previous research described above. However, as for those values, the result is likely to be dependent on the individual subject.

### 3.4. Application of a perceptually relevant time window to the analysis of noise stimuli

When applying the IACC measurement, a decision is needed on the optimum window length to use within the time range of 35 to 243 ms shown in the research.
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Outlined Section 3.3. The value that is used could be a mean value for the subjects used in an experiment (in the case of Boehnke et al [33], the mean of the results was 86 ms), or could be the lowest value to be applicable to the most sensitive subject (from the research reviewed, 35 ms).

For the creation of experimental stimuli for use in a wide range of experiments, it would be preferable to create stimuli that have a constant IACC when measured using the most critical parameters. In this way, the stimuli should be suitable for all subjects, including the most sensitive. Based on this, it seems logical to use a measurement with a window length of approximately 35 ms.

From the results shown in Figure 1, the measurement made using a 50 ms time window is closest to the most critical time window of 35 ms. This measurement shows results over time that cover a range of 0.4, which the authors expect will be larger than the JND of such a stimulus. Therefore, it is apparent that noise stimuli are unsuitable for use as experiment stimuli due to the fact that the IACC varies over time.

4. STIMULUS CREATION TECHNIQUE

As the research outlined above shows that the existing stimulus types do not meet the requirements set out in Section 2, an alternative stimulus is required. An alternative method of creating decorrelated signals is to use either amplitude or frequency modulation, as shown in [16]. An amplitude modulated signal with a given carrier component and a given modulation component has a narrower bandwidth than a frequency modulated signal with the same carrier and modulation components. Therefore it is more likely that an amplitude modulated signal will meet the requirements set out in Section 2.

4.1. Stimulus creation method based on amplitude modulation

Stimuli with a low interchannel cross-correlation coefficient can be created by a process of amplitude modulation and time offsetting. For this, a sine tone carrier of a given frequency is amplitude modulated by a second sine tone, and then the original carrier sine tone is suppressed. The resulting signal is then fed to two channels with a time offset of one quarter of the period of the modulation sine tone in one channel compared to the other. This is shown in Equation 3.

\[
\begin{align*}
    s_1 &= \sin(2\pi f_c t) \sin(2\pi f_m t) \\
    s_2 &= \sin(2\pi f_c [t + t_m]) \sin(2\pi f_m [t + t_m])
\end{align*}
\]

where \( s_1 \) and \( s_2 \) are the two output signals
\( f_c \) is the audio frequency
\( f_m \) is the fluctuation frequency
\( t_m \) is the time offset defined by \( [1/(4 f_m)] \)

This results in a CCC (as defined in Equation 1) between \( s_1 \) and \( s_2 \) of 0 when \( \tau = 0 \). The CCC across a range of \( \tau \) of \( \pm 1 \) ms is dependent on the frequencies of the modulation and carrier sine tones, as the cross-correlation varies away from \( \tau = 0 \) at a rate that is dependent on these. For this reason, it is preferable to use a relatively low modulation frequency.

In order to create stimuli with a range of values of IACC, the two output signals are combined using a similar technique to that employed by Plenge [3]. The two output signals of the stimuli (\( s_1 \) and \( s_2 \)) are mixed in various proportions, one in-phase and one phase inverted, to give the signals that can be reproduced, as shown in Equation 4.

\[
\begin{align*}
    l &= Gs_1 + (1 - G) s_2 \\
    r &= Gs_1 - (1 - G) s_2
\end{align*}
\]

where \( l \) is the left stimulus signal
\( r \) is the right stimulus signal
\( G \) is the gain used to control the relative level of the two signals

The relationship between the gain \( G \) and the interchannel cross-correlation coefficient between the signals \( l \) and \( r \) is constant for the range of carrier frequencies, but is not linear, as is shown in Figure 2.
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Figure 2: Relationship between the gain ($G$) applied to mix the two channels of the amplitude modulated stimuli (as shown in Equation 4) and the resulting interchannel cross-correlation coefficient between the signals $l$ and $r$ measured using Equation 1 at $\tau = 0$.

The relationship shown in Figure 2 can be approximated by Equation 5.

**Equation 5**

Resulting interchannel cross-correlation coefficient

$$=-4.9925G^2 + 9.4886G -3.5125$$

### 4.2. Method of reproducing the stimuli

The interchannel cross-correlation coefficient measurement shown in Figure 2 is simply calculated between the two channels that result from Equation 4 ($l$ and $r$). It is important to consider how this relates to the IACC that is presented at the ears of the listener.

If the signals are presented via headphones, then assuming that the cross-talk between the channels of the reproduction system is low, the IACC of the stimuli should approximately equal the interchannel cross-correlation coefficient.

It would also be useful to be able reproduce these stimuli over loudspeakers in order to judge the subjective effect of sounds that are perceived to be positioned outside the head. Unfortunately, in this case, the signals that arrive at the ears do not necessarily have the same properties as the signals in each of the channels of the stimulus. This is due a number of factors. Firstly, the loudspeakers may not be exactly symmetrical about the median plane of the subject, due either to movement of the subject or incorrect positioning, resulting in a time offset between the signals arriving at the ears. Secondly, the acoustic cross-talk caused by the fact that the sound from each loudspeaker reaches both ears may cause the IACC to be different to the interchannel cross-correlation coefficient of the stimulus. This could give a higher or lower value, depending on the specific interaction between the interaural delay of each of the signals due to the physical separation of the ears and the frequency of the stimuli. Thirdly, unless the experiments are conducted in an anechoic chamber, the reflections from the boundaries and items within the acoustical environment will further alter the properties of the sound that reaches the ears.

If a specific IACC is required, the narrow bandwidth of these stimuli is a disadvantage as there is a greater chance that the factors mentioned above will cause a significant change to the IACC due to the fact that there are only two sinusoidal components. In addition, it is likely that movement of the head will significantly alter the resulting IACC, which will make it difficult to relate a specific IACC to a certain perceived effect. It may be possible to use these stimuli over loudspeakers for certain experiments, as long as the head movement is limited and the IACC to which each subjective judgement relates is closely monitored. However, this will make the experimental setup more complex.

Therefore, whilst these stimuli are suitable for use in headphone reproduction, they are more complex to use in loudspeaker reproduction, and it may not be possible to create the complete range of IACC values.

The remainder of the paper assumes that headphone reproduction is used and therefore the IACC is approximately equal to the interchannel cross-correlation coefficient.

### 5. VERIFICATION

#### 5.1. Bandwidth

As may be expected from amplitude modulation of a sine tone by another sine tone with a suppressed carrier, the stimuli that result consist of two sinusoidal components that are spaced by the modulation frequency away from the carrier frequency [35]. This means that in order for the stimuli to have a bandwidth of less than 35 Hz at low frequencies as specified in Section 2, the modulation frequency needs to be less than 17.5 Hz.

However, it must be noted that there is a side-effect caused by mixing the stimuli as shown in Equation 4.
If $f_c = (2n f_m) - f_m$ where $n$ is an integer and $G = 0.5$, the components are contained individually in each channel, as shown in Figure 3.

![Figure 3: Fast fourier transform (FFT) of the two channels of the stimulus ($l$ and $r$) created using Equation 3 and Equation 4, for a stimulus where $f_c = (2n f_m) - f_m$, $n$ is an integer and $G = 0.5$.](image)

If either $f_c$ or $G$ are slowly changed from the values shown above, the two sinusoidal components gradually appear in both of the output channels until a point at which $f_c = (2n f_m)$ where $n$ is an integer or $G = 1$, at which point the sinusoidal components are of equal level in each of the channels.

Whilst the value of the IACC measured using Equation 1 is similar when $G = 0.5$ whether the components are separate in each channel or combined, the characteristics of the signals are different. For the case where $f_c = (2n f_m)$, the signal level is constant over time as shown in Figure 4, and the low IACC results from the difference between the frequency components in each channel causing a constantly varying phase difference between the channels.

![Figure 4: Plot of the two channels of the stimulus ($l$ and $r$) created using Equation 3 and Equation 4, for a stimulus where $f_c = (2n f_m) - f_m$, $n$ is an integer and $G = 0.5$.](image)

For the case where $f_c = (2n f_m)$, the signal level varies over time at twice the rate of the modulation frequency as shown in Figure 5, and the low IACC results from the fluctuations in the interchannel level difference as well as the phase difference between the channels that changes every quarter of the modulation period.

![Figure 5: Plot of the two channels of the stimulus ($l$ and $r$) created using Equation 3 and Equation 4, for a stimulus where $f_c = (2n f_m)$, $n$ is an integer and $G = 0.5$.](image)

Whilst the differences between these types of signals may not be perceived at lower audio frequencies, they are likely to be perceived at higher frequencies where the human perceptual system fails to track the fine detail of the stimuli. At these frequencies the perceived effect is likely to be dependent on the envelope of the signals, and in this case the signals shown in Figure 4 and Figure 5 will be perceived differently.

These differences between the signals created at different frequencies may cause problems in subjective experiments as they will introduce additional experimental variables unless such effects are taken into account. On the other hand, this side-effect of the stimuli may be useful for investigating...
the perception of fine temporal detail at different audio frequencies.

5.2. Constancy of IACC over time

It is apparent from the specifications in Section 2 and the research discussed in Section 3.3 that, in order that the stimuli can be used for the most sensitive subjects, the stimuli need to have a constant IACC over time when measured using a time window of 35 ms. One method that could be used to keep the stimuli constant within these limits is for the stimulus to repeat on a shorter scale than the measurement window. This can be achieved with the amplitude modulated stimuli by using a value of \( f_m \) whose period is equal to or less than the measurement window. As can be seen in Figure 6, this results in a stimulus which measures as having a constant IACC over time within a tolerance of ± 0.01, which is likely to be within the JND thresholds.

![Figure 6: Variation in IACC over time with a 0.035 second measurement window](image)

**Figure 6: Variation in IACC over time of the amplitude modulated stimuli with \( f_c = 1000 \) Hz, \( f_m = 30 \) Hz and a range of values of \( G \) measured using a series of IACC calculations with a window length of 0.035 seconds overlapping by half the window length.**

However, the stimulus whose measurement is shown in Figure 6 has a modulation frequency of 30 Hz, which results in a stimulus bandwidth of 60 Hz. As discussed in Section 5.1, this means that the stimulus has a bandwidth that is too large to use at low frequencies.

Therefore a compromise must be reached between the bandwidth of the stimuli and the constancy of the IACC over time. As the decision to use a 35 ms window length in the measurement is at the low end of an estimated range from 35 to 243 ms, it is likely that a lower modulation frequency which has a constant IACC when measured with a slightly longer measurement window will affect experimental results less than a bandwidth that is too large at low frequencies. Therefore the authors consider that it would be preferable to use stimuli with a modulation frequency of approximately 20 Hz or lower.

5.3. Ability to create any IACC

It can be seen from the results shown in Figure 2 and Figure 6 that the amplitude modulation method can be used to create stimuli with a wide range of values of IACC, simply by changing the value of \( G \) in Equation 4. However, there are some limitations to the range that can be created.

As mentioned in Section 4.1 the stimuli cannot create an IACC of 0 across the range of \( \tau \) of ± 1 ms for certain stimuli as the measured CCC (as defined in Equation 1) varies from 0 at \( \tau = 0 \) as a function of the carrier and modulation frequencies. This can be seen in the middle plot of Figure 7. Nevertheless, in the majority of cases, the stimuli that are created when \( G = 0.5 \) have an IACC that is below 0.1, which is closer to 0 than the stimuli discussed in Section 3.

As for any stimulus of a relatively high frequency with an IACC value that is non-zero, the CCC of the stimuli that are created using the amplitude modulation method can vary a large amount over the values of \( \tau \) used when measured using Equation 1, as shown in Figure 7. This cannot be avoided as the variation of the CCC over the range of \( \tau \) is related to the periodicity of the measured signal. It must be noted that it is not certain how this would affect the perceived result, as the effect of different patterns in the IACC across the range of values of \( \tau \) has not yet been investigated. However, as this is present in measurements of all narrow-band high-frequency signals, it is not considered to be a problem for these stimuli.

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As discussed in Section 2, the ideal situation would be for two stimuli with different IACC values to have no other detectable differences, though it was acknowledged that it is likely to be impossible to create such stimuli. For the case where $f_c = (2n fm)f_m$ as discussed in Section 5.1, the fact that the two tones separate into the two channels makes this the worst-case scenario for these stimuli. As can be seen in Figure 8, varying the value of $G$ that is used to create the stimuli (which varies the resulting IACC) can vary the frequency characteristics of the signal in each channel, though the spectrum of the sum of the two channels remains broadly similar.

It can be seen from Figure 9 that for stimuli where $f_c \neq (2n fm)f_m$, the differences in the spectral content caused by altering the value of $G$ are smaller, but may still be perceivable.
Therefore it is possible that timbral changes will be perceived when the IACC of the stimuli is altered, however it is likely that these will be small. Even so, these differences may aid a subject in a detection or discrimination experiment that is based on techniques such as two alternative forced choice (2AFC), match-to-sample or method of adjustment. Therefore this must be taken into account when designing the experiment or when analysing the results.

5.4. Variations in IACC over time

As discussed in Section 5.3, the IACC of the amplitude modulated stimuli can be varied by changing the value of $G$ in Equation 4. Therefore by modulating $G$ over time using a chosen function, the IACC of the stimulus will vary in a similar manner. The results of this can be seen in Figure 10, where $G$ varies sinusoidally over a range of 1 to 0.5 at a rate of 3 Hz.

From this analysis it appears that controlled variations in IACC over time can be created using these stimuli, but this process affects the spectral content of the signal and therefore this must be taken into account in the design of the experiment.

5.5. Discussion

It is apparent from the results shown in Section 5 that the stimuli created by the use of the amplitude modulation method do not perfectly meet all the criteria set out in Section 2. However, it has been shown that they meet the criteria more closely than previously used stimuli such as music, speech or noise-based stimuli. As a number of the factors require a compromise between the parameters used to create the stimuli, it is possible for stimuli to be created that focus on the most important criteria for a given experiment by choosing the most appropriate parameters. For instance, if the constancy of the IACC over time is of prime importance, a higher modulation frequency can be used, though this will make the stimuli bandwidth wider than a critical band at low frequencies. On the other hand, if it is of prime importance that the stimuli have a narrow bandwidth, a lower modulation frequency can be used, though this may mean that the IACC is perceived as varying by the most sensitive subjects.

A number of the limitations of the stimuli such as the timbral variations caused by altering the IACC may be problematic, but in most cases the effect of this on the experiment can be avoided by careful experiment design.
As mentioned in Section 4.2, the stimuli that are created can be reproduced over headphones with the resulting IACC being approximately equal to the interchannel cross-correlation coefficient, assuming that the reproduction system has low interchannel cross-talk. It is also possible to use these stimuli for loudspeaker-based reproduction, though in this case the resulting IACC is likely to be different from the interchannel cross-correlation coefficient, and it may not be possible to create the whole range of IACC values. Whilst it will be more complex to use these stimuli with loudspeaker reproduction, it is possible to conduct an experiment in this manner.

It must be noted that the main purpose of the stimuli described above is to investigate the subjective effect of the IACC of continuous as opposed to transient signal types. It is possible that research into the perception of the time-varying IACC will provide useful information about the perception of the IACC of transient signals. It is also possible that short samples of the amplitude modulated stimuli could be used for investigating the perception of transient signals, or that a number of short samples could be combined to investigate the perception of onsets and offsets of sounds. However, this type of combination or modification of the resulting amplitude modulated stimuli is likely to create additional side-effects and the requirements for transient signals for investigating these factors are likely to be different to those requirements set out in Section 2. Therefore it may be more suitable to use an alternative method for creating stimuli to investigate the perception of the IACC of transient signals.

6. APPLICATIONS

The stimuli that are created by the method that is outlined in this paper can be employed in subjective experiments to uncover a number of perceptual aspects relating to the perception of the IACC. A number of possible experiments are listed below.

Firstly, the relationship between a certain IACC value and the perceived width or size at different audio frequencies can be investigated using narrow-band stimuli created using the above method. The stimuli allow for a range of experimental methods to be used such as match-to-sample, method of adjustment or two alternative forced choice (2AFC). As an extension of this, it is possible to make use of the different envelope characteristics of the stimuli that are created at different frequencies to investigate the perceived effect of stimuli whose envelope and fine detail have very different IACC values. The investigation of these parameters can be used to create measurements based on IACC that match the subjective spatial impression of a sound more accurately.

Secondly, the perceived spatial attributes of signals whose IACC varies over time can be investigated in detail with these stimuli. Whilst research has been conducted into the audibility of various temporal variations in the IACC, the resulting perceived spatial attributes of the sounds have not yet been investigated. As the IACC of musical or speech programme material is likely to vary greatly over time as discussed in Section 3.1, in order to accurately relate the perceived spatial attributes of musical stimuli to a measured value, it is important to know how the stimuli with a time-varying IACC are perceived.

Finally, stimuli created by the method outlined in this paper can be used to investigate the just-noticeable-difference (JND) in IACC that is detectable at different audio frequencies. This has been attempted previously by the use of noise stimuli, though finer results may be obtained using these stimuli as opposed to stimuli based on noise where the IACC can vary greatly over time.

In addition to using these stimuli for subjective experiments, they may also be suitable for use as artificial test signals in order to measure the properties of reproduction systems. For instance, test signals with a range of interchannel cross-correlation coefficients can be created in different frequency ranges to test the range of IACC values that can be created at the ears of a listener. Further research is required to investigate the most appropriate method of applying these signals to make a practical and useful measurement.

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8. REFERENCES


